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Patrick Morrissey, Steve Kaye, Chris Martin, Janet Sheung, Shouleh Nikzad, Todd Jones, Jordanna Blacksberg, Michael Hoenk, L. Douglass Bell, "A novel low-voltage electron-bombarded CCD readout," Proc. SPIE 6266, Space Telescopes and Instrumentation II: Ultraviolet to Gamma Ray, 626610 (20 June 2006); doi: 10.1117/12.673208

Event: SPIE Astronomical Telescopes + Instrumentation, 2006, Orlando, Florida , United States

A Novel Low-Voltage Electron-Bombarded CCD Readout

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ABSTRACT

We present proof-of-concept results for a novel ultraviolet-sensitive, photon counting, solar blind detector that has the potential for high QE in a compact low voltage, low power, *unsealed* design. We utilize a delta-doped back-illuminated CCD to read out low energy electrons from a photocathode. In parallel, a new generation of high-QE ultraviolet-sensitive GaN photocathodes is being developed with initial success using delta-doping technology rather than cesiation. In this paper we present results with the new readout using a CsI test cathode, which produces events at under 1000 V accelerating potential.

Keywords: Ultraviolet, Detector, Microchannel plate, EBCCD, GaN

1. INTRODUCTION

The next generation of NASA science missions to perform ultraviolet (UV) studies will require significant improvements in sensitivity. Since space telescope aperture area is unlikely to grow very quickly in the next two decades, detector advances, particularly in quantum efficiency (QE), will be required to make up the bulk of these improvements. UV detectors have lagged behind visible and IR devices in performance, offering the possibility of better instrument sensitivity without the weight and cost increases associated with larger mirrors.

At the present time, MCP-based detectors, with their requisite high voltage (HV) requirements, remain the workhorse of UV astronomy because they are solar-blind, have ultra-low background, and, most importantly, are available. There are other options. Delta-doped charge-coupled devices (CCDs) have been shown to have excellent UV QE, however the broad-band nature of their sensitivity may not be suitable for studies of faint UV sources. Also, the conventional electron bombarded CCD (EBCCD) can access the relatively high QE of opaque photocathodes, but at the expense of high voltage and weight requirements.

We are developing a new type of EBCCD detector that will marry some of the best aspects of these technologies in a proximity-focused, semi-transparent mode resulting in a low-background cathode readout operating at modest voltages in a compact and low-weight package. In parallel, we are addressing the QE issues of semi-transparent photocathodes with a program to delta-dope the surface of a GaN cathode, in effect replacing the normally-required cesium layer with an engineered surface that has the same benefit. The cathode results, which will be discussed in a forthcoming paper, are showing early signs of success and will eliminate the need for ultra-high vacuum sealing processes. This new detector will be solar-blind, photon-counting, and high-QE, with the possibility of very large pixel formats. At the same time, it promises to be robust and comparatively easy to fabricate.

The major features of the detector design are:

- High-efficiency, high-resolution, and low-noise resulting from the marriage of a delta-doped CCD with a novel delta-doped GaN photocathode.

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Space Telescopes and Instrumentation II: Ultraviolet to Gamma Ray, edited by
Martin J. L. Turner, Günther Hasinger, Proc. of SPIE Vol. 6266, 626610, (2006)
0277-786X/06/$15 · doi: 10.1117/12.673208

- Low-voltage operation: Mature CCD delta-doping technology enables low-energy electron detection in the CCD over an order of magnitude below the currently available energy threshold, reducing the required accelerating voltage from 10-15 kV to 0.5-1 kV.
- Low mass: Proximity focusing, enabled by the reduction in detectable electron energy, eliminates large and bulky permanent magnets.
- Easy fabrication with no sealed tube requirement: Our GaN prescription yields a robust, chemically inert, solar-blind photocathode, which is expected to have high efficiency as a semitransparent photocathode.

2. THE LOW VOLTAGE ELECTRON BOMBARDED CCD CONCEPT

The low-voltage EBCCD concept combines a compact, easy to fabricate, proximity-focused architecture with a low accelerating voltage enabled by mature CCD delta-doping technology, which was developed at JPL's Microdevices Laboratory. In this treatment, molecular beam epitaxy (MBE) is used to grow 1.5 nm of single-crystal silicon on the backside of the CCD, while incorporating a sheet of 2×10^{14} boron atoms-cm^{-2} (nominally within a single monolayer of the crystal) at a precise location 0.5 nm from the backside surface.[1] The term "delta doping" in the MBE jargon comes about because the doping profile of high magnitude but narrow width resembles a mathematical delta function. Since the delta-doped layer can be placed within nanometers of the silicon surface, it allows the creation of an extremely thin surface electrode. Figure 1 schematically shows the structure grown on the back surface of a thinned CCD.

While delta-doping was initially developed to modify the bandstructure of back-illuminated silicon CCDs for enhancement of response in the ultraviolet (these CCDs exhibit QE at the theoretical limit in the UV), it has also been shown that delta-doped CCDs can be used as excellent low-energy electron detectors.[2] Furthermore, as will be discussed in Section 4, conceptually similar surface engineering technology can now be used to activate GaN cathodes without the use of cesiation, a major advance.

Our detector concept is illustrated in Figure 2. Photoelectrons generated in the cathode are accelerated (~ 1 keV) toward a back-illuminated delta-doped CCD across a narrow gap, generating as many as 150 electron-hole pairs on impact. Out-of-band photons that illuminate the CCD directly only generate one electron-hole pair in the CCD and can be discriminated against as background noise. In this architecture, we plan to incorporate a next-generation GaN photocathode, which promises to be stable (not requiring cesiation), efficient ($> 25\%$), and solar blind. The energetic photoelectrons penetrate past the surface electrode of the back-illuminated CCD and continue into the low-doped sensitive region. On average one electron-hole pair is produced for every ~ 3.6 eV of incident energy, so each incident photoelectron liberates many signal electrons inside the CCD. Since the noise floor of a moderate-speed CCD is on the order of 5 to 25 electrons, quite modest multiplication is required in order to allow the EBCCD to be single-photon counting. While conventional EBCCDs are potentially very effective solar-blind photon-counting detectors, their use has been limited due to the requirements of large magnets and very high accelerating fields; our device will eliminate both of these issues. The expected gain[2] as a function of incident electron energy is reproduced in Figure 3. Since lateral photoelectron energies are only a few eV, resolutions of 20-30 microns can be achieved with a proximity focused semitransparent photocathode separated from the CCD by a few hundred microns and with a 500-1000V potential. Thus a very compact device is possible.

This detector design is sensitive to out-of-band light by direct illumination of the CCD through the semi-transparent cathode, thus some discussion of the expected red rejection is important. The UV-generated photo-electrons will each produce multiple electrons in the CCD. At 1000 V, the expected gain is 150, rendering each event easily discriminable from out-of-band direct detection events (at ~ 1 electron/photon). Furthermore, the cathode can be gated for a fraction of the readout time allowing a high signal-to-noise direct image component to be easily subtracted. Thus the limitation of the system is reached when the *noise* from bright direct detections is similar in magnitude to the size of a single UV photon detection. For a gain of 150, the visible signal would have to be of order $150^2 = 2 \times 10^4$ larger than the UV signal in order to dominate the signal. This level of red rejection is comparable to the performance of the current NUV standard cathode, Cs_2Te.

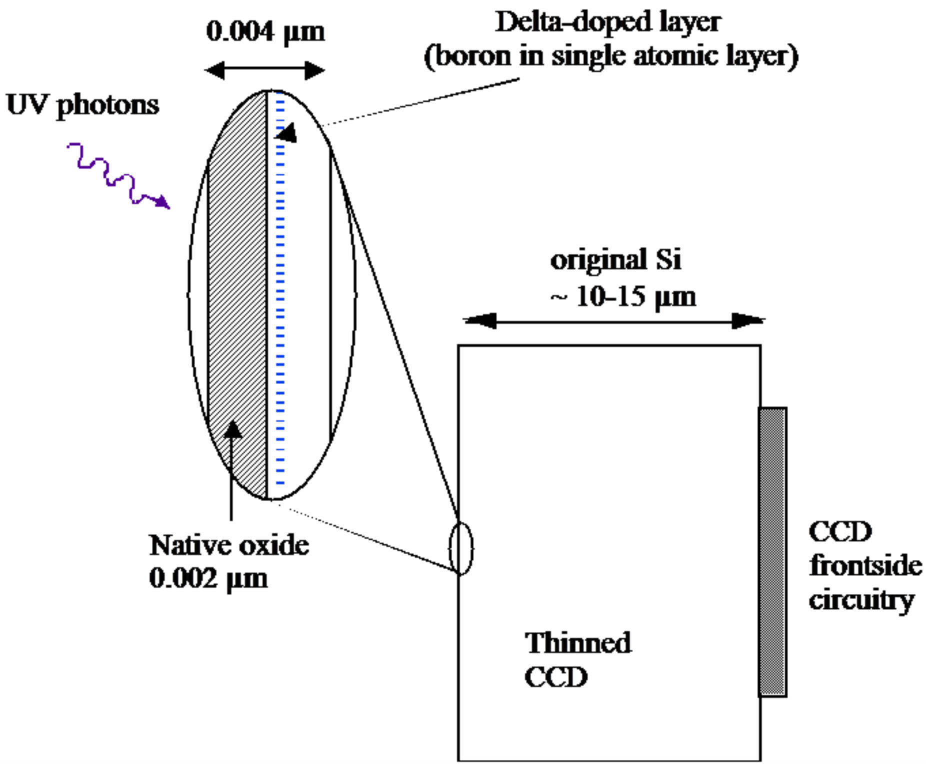

Figure 1. A schematic view of the delta-doped CCD. A monolayer of boron atoms cancels the naturally-occurring field at the oxide-silicon interface, allowing UV-generated photoelectrons and low-energy cathode electrons to be collected by the applied frontside CCD circuitry.

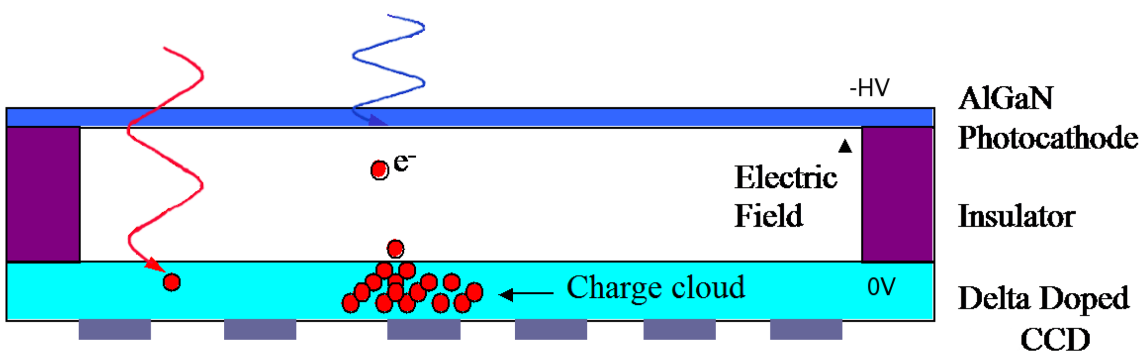

Figure 2. A conceptual view of the low voltage EBCCD. A sapphire window and cathode sits above the delta-doped CCD at an accelerating potential between 500 V and 1000 V. A fraction of the direct light penetrates the cathode and illuminates the CCD, while the remaining light generates photoelectrons in the cathode. Since these photoelectrons are accelerated by the field, they each generate multiple electrons in the CCD and can be discriminated from the direct light image.

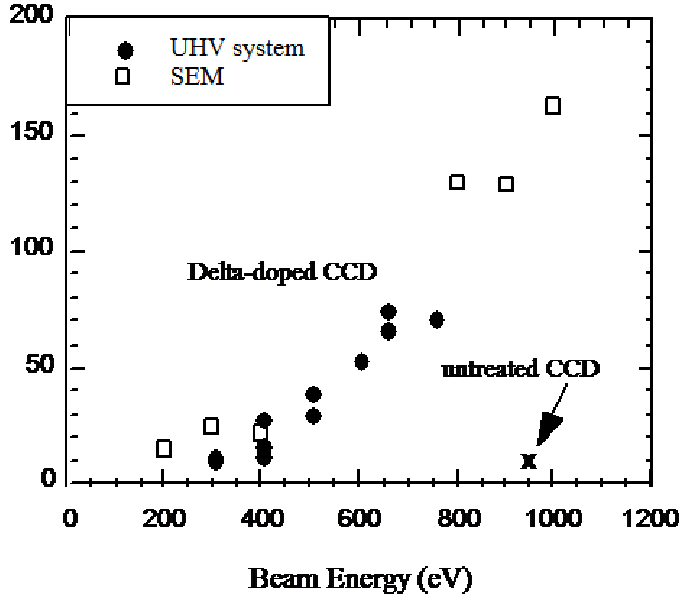

Figure 3. Measured CCD gain versus impacting electron energy.[2]

3. CSI DEMONSTRATION DETECTOR

In order to test our concept we have constructed a demonstration camera utilizing a standard CsI photocathode deposited on a chrome-coated sapphire window and proximity-focused onto a CCD. An assembly view of the camera is shown in Figure 4. The cathode, which is 5 mm in diameter, is mounted inside a hollow screw that enables proximity gap adjustments. Typically the gap is of order 500 microns. The CCD is a back-illuminated Cassini-type 1024×1024, 12 micron pixel device that was thinned and delta-doped at JPL. For these preliminary tests, an engineering-grade CCD with a free-standing membrane is being used, so care must be taken not to damage it with the nearby cathode when making gap adjustments. Because the CCD is back-illuminated, it rests upside-down on the cold plate with the cathode carrier attached to a drilled-through Zero Insertion Force (ZIF) socket.

The electronics were developed for a pulsar-observing camera used at Palomar Observatory.[3] A block diagram is shown in Figure 5. The camera is highly programmable in both voltage level and readout method as enabled by a custom FPGA card with computer interface. The control computer loads firmware into an FPGA. Digital-to-analog converters in the camera head set the voltage levels for the driver signals while the FPGA provides the clock signals. There are three different modes for the clock signals: erase mode, integrate mode, and readout mode. We have been operating the camera in slow scan readout mode for demonstration tests, at a rate of about 100 kilopixels-s^{-1}. The liquid-nitrogen cooled camera head generates the analog video; analog-to-digital conversion occurs in the rack with the FPGA driver. The camera has modest read noise characteristics (in our test configuration it typically runs at about 13 electrons/pixel, but it is capable of much better performance when optimized).

For our tests, we illuminated the CCD with 160 nm (in-band) light from an Acton VM502 monochromator through a vacuum interface. We have characterized the performance of the system using the standard photon transfer technique,[4] which determines the conversion constant to scale from measured digital numbers (DN) to physical electrons collected in each pixel. As the gap voltage is increased, impacting photoelectrons generate larger numbers of detected electrons in the silicon, much the same as when progressively shorter wavelength radiation is detected by the CCD.[5] The photon transfer curve shown in Figure 6 illustrates this phenomenon, however the observed increase in gain from 0 V to 800 V, a factor of ~ 10 as the conversion constant decreases from 1 incident particle-DN^{-1} to 0.1 incident particles-DN^{-1} (reflecting the change in detected electrons generated for

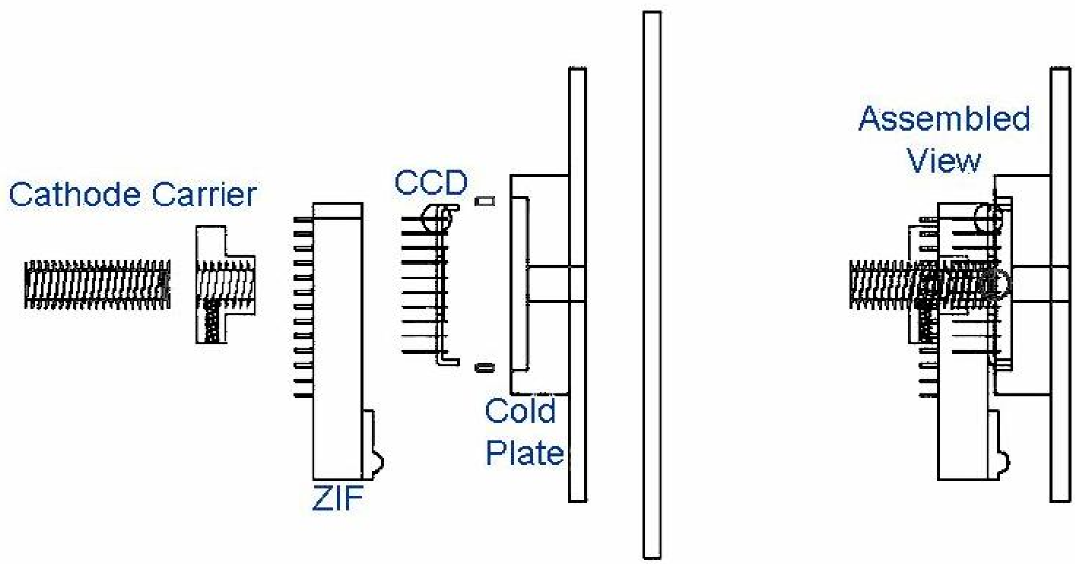

Figure 4. An assembly view of the demonstration version of the low voltage EBCCD. Light enters the system from the left in this drawing. A CsI cathode is deposited on a chrome-coated sapphire window and mounted in a hollow screw (with cathode proximal to the CCD) that allows adjustment of the proximity gap. The delta-doped CCD is illuminated from behind through a hole drilled into the mounting tub and is oriented upside-down on the cold plate. A ZIF socket allows easy reconfiguration.

each impacting electron), underestimates the actual gain increase for several reasons, including that the events are multi-pixel and that each image is a composite of direct (low gain) and indirect (high gain) events observed by the CCD. The actual gain of the cathode events is consistent with the expected value shown in Figure 3 based on the magnitude of individual events detected in Figure 7.

We have also derived a pulse height distribution for the detector by reducing the illumination level so that cathode events in each image do not overlap, and then reading out many frames to generate reasonable statistics. The distribution of pixel values found in each image (using only a 100×50 region of the CCD illuminated by the cathode) is shown in Figure 8. Since the UV photoelectron events on the CCD are larger than a pixel, the individual images have been optimally smoothed (3×3) to match the effective pixel size to the event size (thus reducing the read noise without affecting the event size). While post-process smoothing reduces the read noise, reading out the camera in a 3×3 binned mode would not only perform this function but also increase the magnitude of the events by integration, separating them further from the read noise floor without increasing the voltage. As is evident from the figure, the photocathode events are easily distinguished from the background at well under 1000 V. While the CCD read noise could be optimized in our slow-scan arrangement, this demonstration provides a reasonable approximation of a moderate-noise system being framed rapidly for high count rate imaging.

4. PROGRESS ON NON-CESIATED GAN

In this section we will briefly discuss our parallel program to develop the next generation of solar blind UV sensitive photocathodes based on stable, *non-cesiated* GaN (results will be presented in a forthcoming paper). In the past several years there has been a great deal of interest in GaN and its alloys because of the potential for very high quantum efficiency. GaN-based photodetectors are theoretically capable of QE as high as 90%

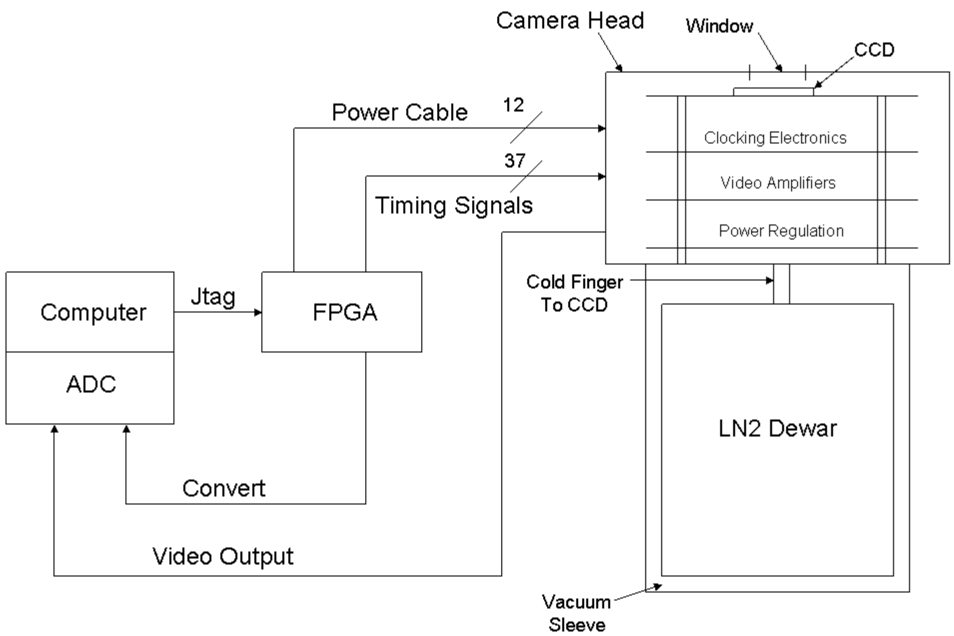

Figure 5. A block diagram of the EBCCD camera electronics.

at 250 nm,[6] with a naturally large (and tailorable) band gap. While a great deal of improvement has been demonstrated in the quality of the GaN material, the inherent noise is still too high to be competitive with other types of detectors. On the other hand, when used as a photocathode GaN seems likely to be able to improve on the modest performance of the near ultraviolet standard, Cs_2Te. Nonetheless, one of the demands of many presently available cathodes, including GaN, is the requirement for activation with cesium. Because of the reactivity of this material, sealed tube technology with its stringent process requirements is necessary for stability. We are exploring methods of *engineering* the GaN surface in order to produce the effect of cesium in a more stable configuration. One such alternate method for producing a surface dipole is through delta doping. New advances in materials growth, including some of our recent results, are making it possible to achieve ultrathin near-surface high charge concentrations of dopant materials. This is a similar process as used for the CCD, but conceptually "backward," enabling electrons liberated from the cathode surface to escape into the vacuum. Thus we are developing a fully-depleted delta-doped photocathode housed in GaN. Unlike the cesiated photocathodes mentioned above, this design does not require an unstable, low work-function metal coating. Instead, the cathode consists of a p-GaN substrate with an n-type (Si) delta layer in close proximity to the surface (a few nm). Electrons that are photogenerated in the bulk p-type region can diffuse to the depletion region, whereupon the large built-in fields accelerate them toward the surface. Provided the photoelectrons do not scatter inelastically during this transit, they reach the surface with sufficient energy to escape into the vacuum.

Thus far we have demonstrated a reduction of escape threshold energy similar to that achieved in cesiated photocathodes. Furthermore, we have shown improvement in the efficiency by optimization of the layer design. Future iterations may also include incorporation of an additional *piezoelectric* band-bending made possible by the addition of Al (which will also have the effect of modifying the cathode band edge). Early results with non-cesiated, delta-doped GaN in opaque mode are encouraging, with QEs of order a few percent at the early stages of development.

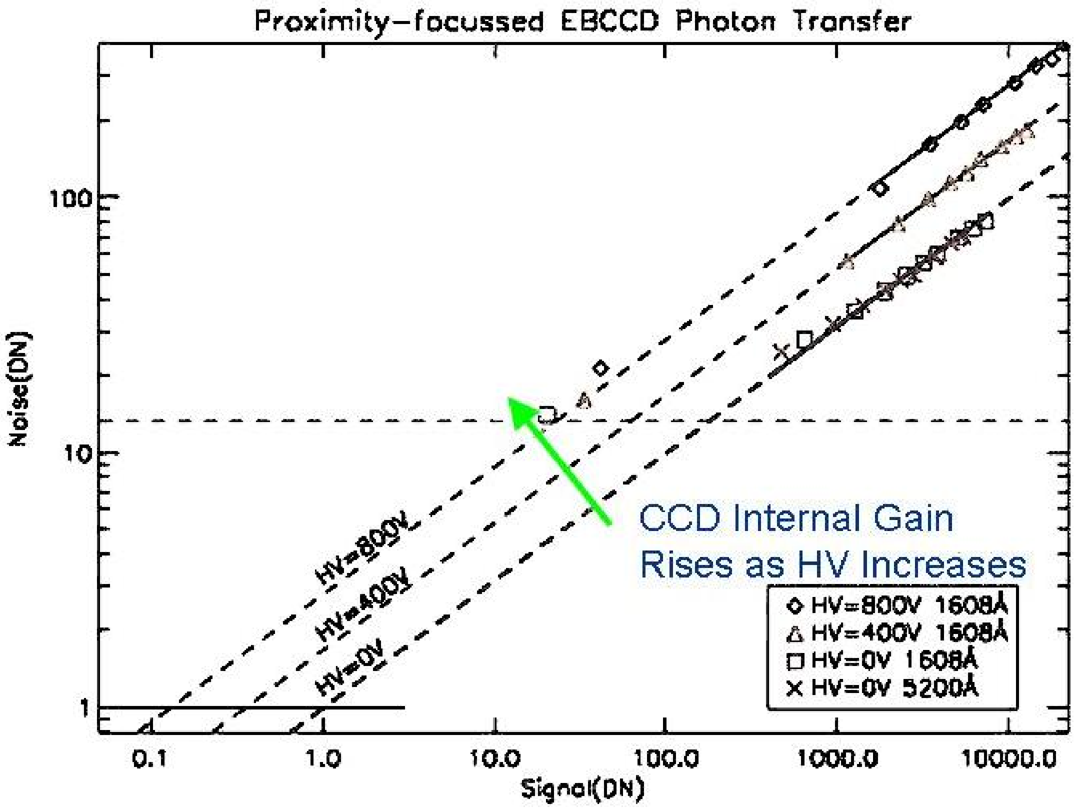

Figure 6. Photon transfer curves taken at several cathode voltages for the demonstration system using a CsI cathode and 160 nm illumination. Because the photon transfer analysis combines the direct and cathode inputs, it significantly underestimates the gain of the injected electron events from the cathode.

5. CONCLUSIONS

The future of ultraviolet astronomy will depend on detectors with stable and high quantum efficiency, high dynamic range, and low noise in order to improve performance without large increases in instrument mass (and cost). In addition, due to the requirements for smaller and more frequent missions, these detectors will also need to be compact, low power, and robust for the space environment. Our EBCCD concept represents a significant step toward these goals with voltage levels an order of magnitude lower (0.5-1 keV vs. 10-15 keV) than a conventional EBCCD and in a far lighter package. Because of the stability of the engineered GaN photocathodes being developed in our parallel program (with no need for cesiation or sealed tube technology), the EBCCD will be far less costly and time-consuming to fabricate. Lower voltage requirements than either MCP or conventional EBCCD detectors also represent a step toward a more rugged design. Furthermore, mosaicing the delta-doped CCD could enable very large pixel formats (as large as 8000×8000).

In this demonstration, we have shown that the delta-doped CCD is capable of easily discriminating in-band photon events from low-level direct background at low voltage (< 1000 V). Our non-cesiated GaN cathode results also appear promising. Remaining work includes characterization of the system resolution as a function of gain, and incorporation of a non-cesiated GaN cathode.

ACKNOWLEDGMENTS

This work was funded by a Planetary Instrument Definition and Development grant from the National Aeronautics and Space Administration, and by the Aerospace Corporation (El Segundo, CA), which provided funding for J. S.'s Caltech Summer Undergraduate Research Fellowship.

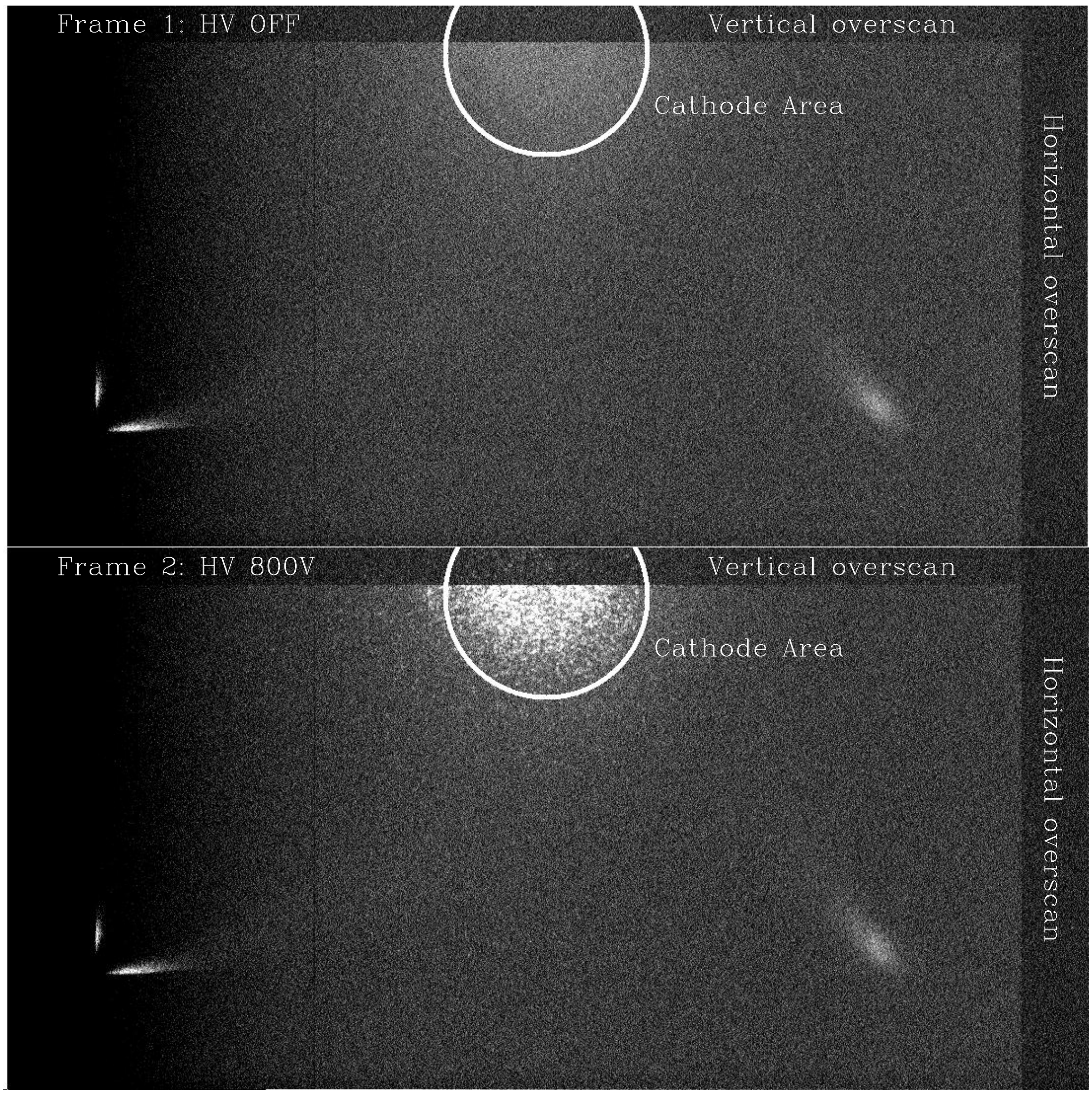

Figure 7. *Top image:* The direct-illumination component in our laboratory system observed with the high voltage off. *Bottom image:* The photocathode contribution with the high voltage switched on under identical illumination conditions. Note that our engineering-grade device is only 1/2 active, so while the photocathode (marked with a circle) is centered over the physical device we only see about half of it.

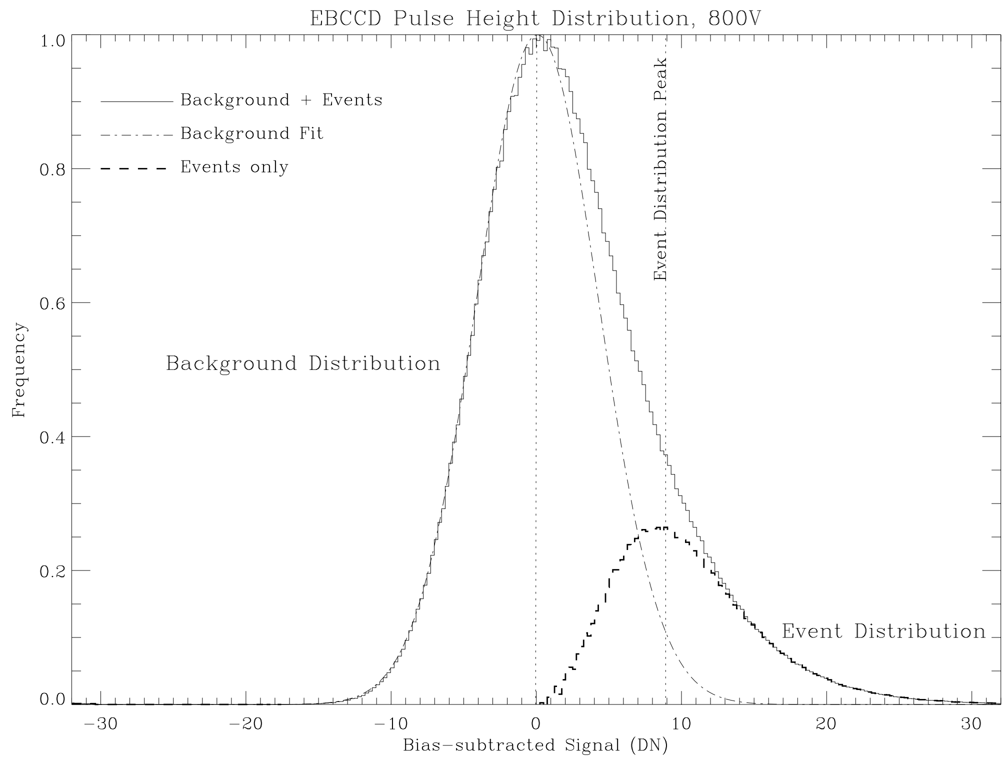

Figure 8. *Solid line:* A histogram of pixel values collected from a series of 3×3-smoothed images with the high voltage switched on (800 V). *Dot-dash line:* A Gaussian fit to the left half of the histogram, revealing an excess of high signal events from the cathode. *Dashed line:* The pulse height distribution of photocathode events, which is the difference of the total image signal distribution and the fit to the background component. Since these events are multi-pixel, a binned CCD readout would further increase their separation from the background noise. Even in our relatively noisy camera system (~ 13 electrons), the events are easily isolated.

REFERENCES

1. M. Hoenk *et al.*, "Growth of a delta-doped silicon layer by molecular-beam epitaxy on a charge-coupled device for reflection-limited ultraviolet quantum efficiency," *Appl. Phys. Lett.* **61**, p. 1084, 1992.
2. S. Nikzad *et al.*, "Direct detection and imaging of low-energy electrons with delta-doped charge-coupled devices," *Applied Physics Letters* **73**, p. 3417, 1998.
3. B. Kern, *Optical Pulse-Phased Observations of Faint Pulsars with a Phase-Binning CCD Camera*. PhD thesis, California Institute of Technology, Pasadena, CA, 2002.
4. J. Janesick, *Scientific Charge Coupled Devices*, SPIE Press, Bellingham, WA, 2001.
5. P. Morrissey *et al.*, "Vacuum-ultraviolet quantum efficiency of a thinned, backside-illuminated charge-coupled device," *Applied Optics* **34**, p. 4640, 1995.
6. C. Joseph, "Advances in astronomical UV image sensors and associated technologies," in *Photodetectors: Materials and Devices II*, G. Brown and M. Razeghi, eds., *Proc. SPIE* **2999**, 1997.